soil systems

Article

Enhancing Corn Yield and Soil Quality in Irrigated Semiarid Region with Coal Char and Biochar Amendments

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Abstract: Sustainable use of croplands is facing a challenge to maintain organic carbon (C) in soil. Pyrolyzed coal or coal char (CC) is a porous C material produced from the pyrolysis of coal containing high organic C, large surface area, and low bulk density like biochar (BC). This study evaluates corn (*Zea mays* L.) grain yield and selected soil properties in soil amended with CC and BC at two rates (22 and 44 Mg ha^{-1}) with farmyard manure (FM) (66 Mg ha^{-1}) and without FM addition. This field experiment was performed in sandy loam soil at the University of Wyoming's Sustainable Agricultural Research and Extension Center (SAREC), Lingle, WY, USA. Two years of field study results indicated CC and BC applied at 22 Mg ha^{-1} with FM resulted in significantly greater average corn grain yields (13.04–13.57 Mg ha^{-1}) compared to the no char's treatment (11.42 Mg ha^{-1}). Soil organic matter (SOM) content was significantly greater in the higher application rates of CC and BC than in treatments without chars. Overall, soil nitrate nitrogen (NO_3-N), phosphorous (P), and potassium (K) were found significantly greater in CC and BC co-applied with FM treatments. Soil water-holding capacity (WHC) significantly improved in sandy loam soil (up to 27.6% more than the no-char treatment) at a greater concentration of char materials. This study suggests that char materials applied at a moderate rate (22 Mg ha^{-1}) with FM can improve soil properties and crop yield.

Keywords: coal char; biochar; corn yield; soil amendment; soil quality

Citation: Thapa, R.B.; Budhathoki, S.; Shilpakar, C.; Panday, D.; Alsunuse, B.; Tang, S.X.; Stahl, P.D. Enhancing Corn Yield and Soil Quality in Irrigated Semiarid Region with Coal Char and Biochar Amendments. *Soil Syst.* **2024**, *8*, 82. https://doi.org/10.3390/soilsystems8030082

Academic Editor: Yam Kanta Gaihre

Received: 23 May 2024
Revised: 10 July 2024
Accepted: 11 July 2024
Published: 15 July 2024

1. Introduction

Modern agricultural practices for increasing crop productivity to feed the growing human population can adversely impact soil health and the environment. Intensive tillage in cropping systems, substantial use of inorganic fertilizers and pesticides, and rigorous use of heavy equipment in farmland are some major factors causing soil health degradation worldwide [1]. The continued likelihood of SOM loss due to certain farming practices can seriously threaten soil properties and long-term sustainable cropping systems [2]. Crop production without degrading soil health or harming the environment is a critical concern for sustainable agriculture [3,4]. The low soil organic carbon (SOC) content is challenged to achieve optimum productivity, especially in semiarid agroecosystems. Semiarid soils are characterized by low SOC content and high spatial and temporal variation in precipitation [5]. Goshen County in eastern Wyoming (WY) lies on the western edge of the semiarid Great Plains, and soils in the area are characterized by low SOC content and inherently low soil fertility.

Adding carbon (C)-rich materials such as coal char (CC) and biochar (BC) is regarded as an effective strategy that has been successfully adopted to ameliorate soil properties and enhance SOC, ultimately increasing crop yields [6]. Conventional methods for soil improvement include the application of different types of manures such as solid and liquid cow's, pig's, poultry manures, and compost to increase soil productivity; however, their applications have been limited due to the increased dissolved organic carbon (DOC) and elevated phosphate (PO_4^{3-}) leaching, resulting in soil greenhouse gas (GHGs) emissions through stoichiometric relations with C [7]. In conventional agriculture, different types of manures, such as solid farmyard manure (FM) from pigs, cows, horses, poultry manures and composts, and liquid manures, are used to enrich the soil with nutrients and organic matter. During animal production, the storage of manures produced during that time, and during their application to the soil, odorous, volatile organic compounds (VOCs), ammonium (NH_4), hydrogen sulfide (H_2S), and potent greenhouse gasses such as methane (CH_4) and carbon dioxide (CO_2) are emitted [8]. At the initial stage of FM application, it may lead to a temporary yet substantial increase in the atmospheric emissions of potent GHGs such as nitrous oxide (N_2O) and methane (CH_4). Due to the microbial degradation of DOC that reduces the oxygen (O_2) content in the soil, this effect is attributed to the transient formation of the soil redox environment promotes CH_4 production and denitrification leading to the production of N_2O [7,9]. Inorganic nutrients and DOC can be highly mobile in soil and susceptible to leaching [10], which could affect nutrient cycling. In any agroecosystem, nutrient cycling is a critical process that keeps nutrients flowing through abiotic and biotic components of ecosystems and makes nutrients available for use by plants, animals, and microbes [11,12]. It can be predicted by several factors: SOC, NH_3 volatilization, dissolved organic matter (DOM), DOC, and soil–microbial interactions [13–15].

A similar product, BC, produced by the pyrolysis of plant biomass under oxygen-limiting conditions, has become a popular soil amendment product for extensive research on sustainable agricultural practices that improve SOC, soil properties, and crop yields due to its high surface area, which increases the capacity of soil sorption complex and increasing reactive sites, allowing for the binding of the macro and micronutrients [16–18]. Applying BC to the soil usually increases SOC concentration and enhances the associated soil properties [19,20]. The addition of BC to soils can increase SOC via direct and indirect effects; the quantity of stable C added to the soil represents the direct effects, while negative priming (the potential reduction in the mineralization of native SOM) refers to the indirect effects [21–23]. BC application not only increases soil C concentration, as suggested by Backer et al. [24], but also contributes to C sequestration [23], reduces soil bulk density [25], and increases water infiltration and retention [26]. Several other studies have reported the ability of BC to improve soil structure via enhanced aggregation and increased nutrient retention [7,27]. An experimental pot study performed on coarse-textured soil suggested that BC obtained from straw enhanced the plant's available water by 28% [28]. An incubation study performed on soil amended with BC derived from maize straw led to a substantial reduction in C losses, ranging from 16 to 53%, compared to unamended soils [29]. BC consists of several nutrient salts (Na^+, K^+, Ca^{2+}, etc.) and acts as a slow-release fertilizer [30], by releasing these nutrients at different variable rates in the soil that benefits the soil microbial communities [31]. Palansooriya et al. [32] suggested that the significant porosity and sorption capacity of BC allows it to bind crucial nutrient cations, ultimately making it more available for microorganisms. Cooper et al. [33] concluded that BC applications to soil can increase soil microbial biomass through priming effects. BC application on a large scale for farmers can be challenging and cost-restricted due to its relatively high production costs [7,34,35].

As a soil amendment, CC shares some similar physical characteristics with BC [36]. The use of chars (CC and BC) could increase nutrient holding capacity and increase the cation exchange capacity (CEC) of soil, thus boosting the potential productivity of soil. Similar studies have shown that char comprises C-rich organic amendments that can help regenerate soil C and constitute the essential nutrients for plant growth for sustainable agriculture [18,34]. Coal combustion residues (CCRs) have been widely used as a potential soil amendment to improve soil health, increase crop yields, and promote agricultural sustainability [37,38]. Panday et al. [39] used CCRs (coal char) that contain approximately 29% C by weight and found that CC applied at the rate of 10.1 t C ha^{-1} (CC measured in C equivalent) in fertilized sandy loam soil reduced NH_3 volatilization by 37% compared to control soil. These results indicated the efficiency of CC in nutrient retention in soil and its environmental benefits. There was a further increase in SOC by more than 8% when the char application rate was increased to 13.4 t C ha^{-1} [34]. Low-rank coal, characterized by low heating value, high moisture content, and greater humic substances, has the potential as a soil amendment that could improve soil quality [40]. Granules or powder products derived from low-rank lignite coal can be used for slow-release nutrient products in agricultural land due to their extensive surface area and porous structure [40–42].

Organic C in chars may not be mineralized or used as a C source by soil microbes due to recalcitrant C in it, which is resistant to microbial decomposition [43]. Recent studies mentioned that BC applied with organic material containing labile C, such as compost and FM, could produce positive synergistic effects by providing nutrients from the decomposition of labile organic matter (OM) sources [16,33,44]. Several studies have been carried out in the past using BC alone and with FM in the agricultural field; however, CC use as a soil amendment is a novel idea as an alternative and clean use of coal in the agroecosystem. Furthermore, evaluations of crop yield using CC and BC in the same field as different treatments were not conducted before in semiarid climatic conditions.

To our knowledge, this is the first paper reporting the field demonstration results for corn yields by applying the CC and BC alone, co-applied with FM at larger fields, and applied at different rates in semiarid regions. Hence, the core objective of this study was to evaluate the potential use of CC as a soil amendment by examining its effects on soil properties and corn yield in irrigated sandy loam soil. We hypothesized that CC and BC mixed with FM could increase corn yield in sandy loam soil. Also, we further hypothesized that semiarid regions with low C-containing soil, where char materials are used as a soil amendment, could increase soil water-holding capacity (WHC) and SOC with char's inherent properties of high C and porous nature.

2. Materials and Methods

2.1. Experimental Site Description

This field study was conducted during the cropping seasons of 2021 and 2022 at the University of Wyoming's Sustainable Agricultural Research and Extension Center (UW SAREC, Lingle, WY, USA) in Goshen County of eastern Wyoming (42.13° N 104.39° W) situated at about 1272 m elevation. The soil in this study area is classified as Haverson and McCook loams (Soilweb, USDA-NRCS). These soils have slightly alkaline characteristics ~pH (7.6 to 8.2). This area has a growing season from May to October and a long, cold winter with snow-covered soil from November to April. The average annual precipitation and temperature during the site's farming season were recorded at approximately 368 mm and 16 °C, respectively, for the year 2021. Weather data were extracted from the Wyoming Agricultural and Climate Network (WACNet), Lingle 2W station, and presented in Figure 1.

The physical and chemical properties of the soil at our experimental site before the study were analyzed and presented in Table 1. Soil pH and electrical conductivity (EC) were measured with a 1:1 ratio of air-dried soil water [45]. The loss-on-ignition (LOI) method was used to determine SOM [46]. The potassium chloride extraction (KCl) method was used to extract NO_3-N from the soil samples [47]. Soil P was determined by the Olsen Bicarbonate method [48], and soil K, Ca, and Mg were extracted using the ammonium acetate (NH_4OAC) method [49]. The soil was slightly alkaline due to the low precipitation and low organic matter of the semiarid climate. Most soil particles were sand, followed by silt and clay, respectively, comprising the sandy loam soil texture.

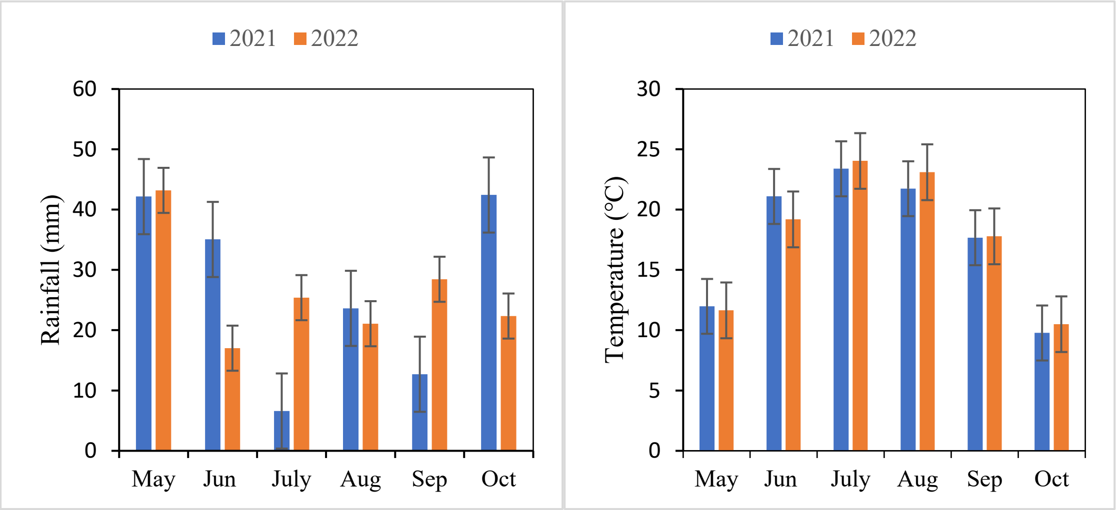

Figure 1. Average monthly temperature and cumulative monthly rainfall during crop growing season in 2021 and 2022 in the study site.

Table 1. Selected soil properties of the experimental corn field prior to treatment application.

Properties	Value
pH (1:1)	8
EC (ds m^{-1})	1.23
SOM (%)	2.53
NO_3-N (mg kg^{-1})	7.73
P (mg kg^{-1})	40
K (mg kg^{-1})	347
Ca (mg kg^{-1})	2977
Mg (mg kg^{-1})	339
CEC (meq 100 g^{-1})	20.13
Soil texture (Hydrometer method)	Sandy loam
Sand (%)	53
Silt (%)	33
Clay (%)	14

2.2. Coal Char, Biochar, and Farmyard Manure

The CC used in this study was made by Atlas Carbon LLC (Gillette, WY, USA), which was produced by the pyrolysis of sub-bituminous coal from the Powder River Basin (PRB) to the temperature of approximately 800 °C under oxygen-limited conditions. BC was commercially purchased from Biochar Now (Berthoud, CO, USA) and was shipped to the university facility. The production of BC used in the study was from a slow-pyrolysis kiln using feedstock of dead wood pine chips and bark under oxygen-limiting conditions at about 600 °C. The FM used in this study was a product of the UW SAREC cattle feeding facility. The selective physical, chemical, and other properties of the CC, BC, and FM used in this study were analyzed using the methods presented in a previous study [36] and are presented in Table 2.

Table 2. Selective physical and chemical properties of CC, BC, and FM used in the study.

Parameters	CC	BC	FM
Dry Matter—Total Solids, %	95.6	98.5	93.3
Moisture, %	4.4	1.5	6.7
EC (ds m^{-1})	7.5	0.14	38.4
pH 1:1	9.6	8.93	7.6

Table 2. *Cont.*

Parameters	CC	BC	FM
Organic Nitrogen, mg kg^{-1}	9300	5280	10,100
Ammonium, mg kg^{-1}	10	2.1	60
Nitrate, mg kg^{-1}	<10	<10	2500
Total Nitrogen, mg kg^{-1}	9310	5282	12,700
Phosphorus as P_2O_5, mg kg^{-1}	1700	3200	11,200
Potassium as K_2O, mg kg^{-1}	500	1400	27,700
Organic C (%)	78.87	87.4	42.36
C/N Ratio	84.5	NA	6.9
Sulfur, mg kg^{-1}	4700	NA	4500
Calcium, mg kg^{-1}	24,300	NA	48,900
Magnesium, mg kg^{-1}	4100	NA	13,100

NA = data not available.

2.3. Study Design and Amendments Application

A randomized complete block design was used for the experiment with 10 treatments, each replicated 4 times, giving a total of 40 different experimental plots (plot size: 4.5 m × 7.5 m = 33.75 m^2 per plot) that accounted for a total plot area of 1350 m^2 (33.75 m^2 × 40 plots). Soil amendment materials (CC, BC, and FM) were applied only in the first year. Two different rates of CC and BC of 22 and 44 Mg ha^{-1} were applied in the field plots. FM was applied at 66 Mg ha^{-1} where required. For treatments that required FM co-application with CC or BC, FM was mixed (properly rolled and mixed with the help of a front-end load tractor and skid steer) outside of the field area and kept in a pile (covered with tarp) for three weeks before application in the research plots. The FM-only treatment plots were applied with FM, directly spreading FM onto them. Soil amendments were applied in the respective plots before seeding during the second week of May at the beginning of the 2021 growing season (Figure 2), using the tractor (John Deere, 7810, Waterloo, IA, USA) equipped with front-end loader, and were evenly spread with hand rakes onto the soil surface. A vertical tiller incorporated soil amendment materials into the top 15 cm of soil. Corn seed (*Pioneer hybrids, 9188 AMTX*) was sown during the last week of May of 2021 and 2022 by using a John Deere 7300 Planter (Moline, IL, USA). Figure 2 shows the image of experimental plots during BC and CC application. Detailed experimental information and field demonstrations for various treatments are given in Table 3.

Figure 2. Picture of the plots during the application of soil amendment materials.

Table 3. Detailed experimental conditions for the different types of treatments applied at different rates in corn fields for the field study.

Treatment Types	CC and BC Application Rate (Mg ha^{-1})	FM Application Rate (Mg ha^{-1})
Control	0	0
FM	0	66
CC	22	0
	44	0
	22	66
	44	66
BC	22	0
	44	0
	22	66
	44	66

0 indicates no application of soil amendment materials (CC, BC, FM).

All treatments received the same quantity of NPK inorganic fertilizer nutrient elements over the years. However, the nutrient application rates in years 1 and 2 are different due to the recommendations provided by the soil testing lab in 2021 and 2022. The different types of fertilizer elements used in the experimental plots are given in Table 4. The strip tiller was used at the beginning stage of the fertilizer applications before planting. Additional fertilizers were applied during planting, followed by the final side dressing in the last week of June before the rows closed. The corn field was irrigated weekly (lateral/linear sprinkler) based on the moisture requirement. The total estimated irrigated water in each plot during the growing season was recorded to be approximately 58.50 cm. Field corn harvests were conducted nearly six months after sowing the corn seed, around mid-November of the respective years, at the 99 BBCH scale of development stage. After harvesting corn in the year 2021, the field was left fallow until sowing corn in May of 2022 because of the cold and snow-covered field in the winter.

Table 4. Types and quantity of different inorganic fertilizers applied at different application timings in the experimental field.

Cropping Seasons	Fertilizers	Application of Nutrient Elements (kg ha^{-1})		
		Strip Tiller	Planter	Vertical Tiller Side Dress
Spring 2021	Nitrogen	47.10	44.83	112.10
	Phosphorus	17.93	8.97	x
	Potassium	9.72	8.7	x
	Sulfur	x	11.21	23.51
Spring 2022	Nitrogen	71.73	60.51	112.10
	Phosphorus	35.87	17.93	17.93
	Potassium	6.71	x	x
	Sulfur	x	7.85	7.85

x indicates no application.

2.4. Soil Sampling

The JMC Backsaver N-2 handle soil core from Clements Associates Inc. (Newton, IA, USA) was used to take the soil samples during the middle of growing seasons (July of 2021 and 2022) from the top 15 cm soil depth for soil WHC and chemical analysis (soil pH, EC, SOM, CEC, NO_3-N, P, K, Ca, and Mg). Four core soil samples were taken randomly from each plot and kept in a Ziploc bag to make a composite soil sample. The composite soil samples were then taken from the field, air dried, and sieved through 2 mm in size using the American Standards for Testing of Materials standards (ASTM). Finally, dry soil samples were sent for analysis to the Soil and Water Testing Laboratory at Colorado State University (CSU, Fort Collins, CO, USA), and analyzed following the methods explained above in Table 1.

2.5. Soil Water-Holding Capacity

One year after the application of char materials in the field, soil WHC was measured following protocols used in previous studies [50,51]. The reason for waiting a year to assess soil WHC on the char treatments was to allow time for more interaction of chars with soil. Soil WHC was determined using dry soil weight vs. saturated–drained (field capacity) soil weight. Initially, soil samples collected from experimental plots were oven-dried at 105 °C for 48 h using the ASTM standards, and the dried weight was measured. The oven-dried soils were then placed in filter paper in a 20 cm funnel and saturated with water. The excess water on the saturated soil was allowed to run through the funnel for 24 h until drainage was complete. The funnel surface was covered with plastic wrap to prevent moisture evaporation. Atmospheric pressure on the soil surface was maintained through holes made in the plastic wrap. After 24 h, the wet soil was removed from the filter paper and weighed immediately. A saturation period of 24 h homogenized water content throughout the soil samples [52], and the soil WHC was evaluated. The difference between the dry weight of the soil before wetting and the net wet weight after removal from the filter paper will give the soil WHC. The mathematical expression has been represented in Equation (1).

$$WHC\ (\%) = \frac{weight\ of\ saturated\ drained\ soil\ (24\ h) - weight\ of\ oven\ dry\ soil}{weight\ of\ oven\ dry\ soil} \times 100\% \quad (1)$$

2.6. Statistical Analysis

Statistics were carried out with RStudio 2022.12.0+353. The Shapiro–Wilk test was carried out to ensure the normality of residuals. Levene's test was used to check the assumptions of homoscedasticity. When the assumptions were not met, inverse transformations were applied to meet parametric assumptions. When normality assumptions failed, data were rank-transformed to run a non-parametric analysis of variance [53]. A three-way analysis of variance (ANOVA) was conducted to determine the effect of amendments, FM, and year on corn grain yield and soil chemical properties. The main effects were amendments (no amendment added; CC 22-Mg ha^{-1}; BC 22-Mg ha^{-1}; CC 44-Mg ha^{-1}; BC 44-Mg ha^{-1}), FM (with FM: +FM and without FM: 0FM), and year (2021 and 2022). ANOVA models were run to assess the main effects and interaction of the factors on corn grain yield, soil pH, EC, OM content, CEC, NO_3-N, P, K, Ca, and Mg. Fisher's LSD test were applied for post-hoc comparisons of the treatment effects in ANOVA at $\alpha = 0.05$.

3. Results

3.1. Corn Grain Yield

The corn yield significantly varied among the amendments, FM application, and years during the two-year growing season (Table 5). No Amendment (A) x Manure (M) x Year (Y), A x M, A x Y, or M x Y interaction was observed. In general, char and manure application positively impacted corn grain yield (Figure 3). BC_22 resulted in ~11% yield increase while CC_22 resulted in a 10% yield increase compared to treatment with no amendments. A two-year grain yield with manure application resulted in a ~6% increase in grain yield. Grain yield was significantly higher in +FM treatments (12.36 Mg ha^{-1}) compared to 0FM treatments (11.68 Mg ha^{-1}). The yield in 2022 decreased by 11% compared to 2021 for all treatments. Grain yield was 12.96 Mg ha^{-1} in 2021, while 11.09 Mg ha^{-1} in 2022.

Table 5. Analysis of variance for grain yield, soil properties, and soil nutrients under effects of amendments, manure application, and year effect with their interaction in corn field.

Source of Variance	Yield	pH	EC	OM	CEC	NO_3-N	P	K	Ca	Mg	WHC
Amendment (A)	**0.001**	0.063	0.133	**<0.001**	0.217	0.146	0.336	0.118	0.274	0.061	0.03
Manure (M)	**0.023**	0.107	0.377	0.054	0.389	**0.033**	**<0.001**	**<0.001**	**0.003**	**<0.001**	0.204
Year (Y)	**<0.001**	**<0.001**	0.902	0.755	**<0.001**	**<0.001**	0.249	**0.014**	**<0.001**	0.389	-
A X M	0.163	0.283	0.074	**<0.001**	0.652	0.521	0.247	0.088	0.087	0.126	**0.018**
A X Y	0.139	0.183	0.035	**0.046**	0.085	0.65	0.514	0.641	0.14	0.184	-
M X Y	0.589	0.718	0.884	0.169	0.056	0.247	0.344	0.202	0.394	0.238	-
A X M X Y	0.272	0.502	0.348	0.396	0.575	0.346	0.892	0.758	0.731	0.932	-

Note: Significant sources of variance for each *variable* at α = 0.05 are indicated in bold letters.

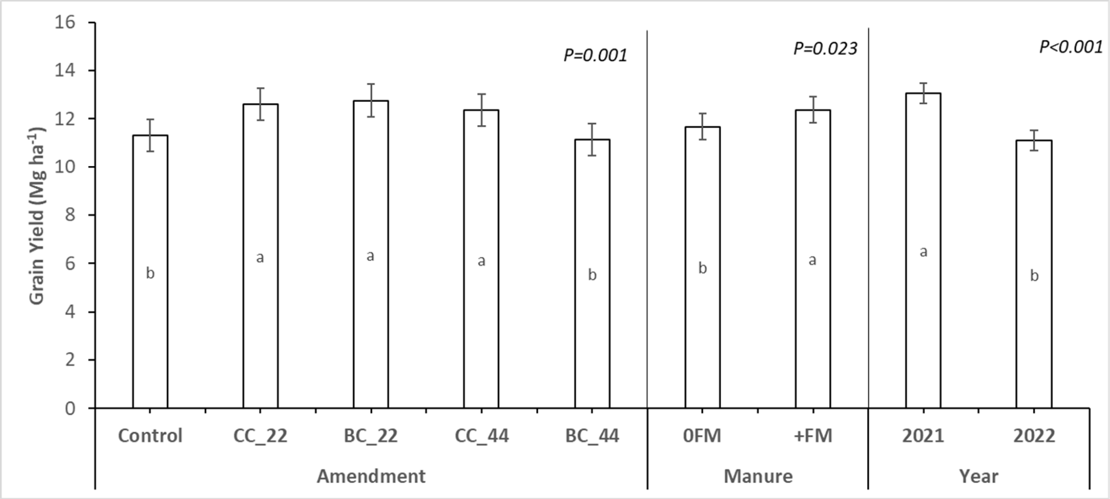

Figure 3. Effect of amendments, manure application, and year on corn grain yield. Means followed by the same letters within columns are not statistically different ($p > 0.05$, *Fisher's LSD test*). 0FM: without FM; +FM: with FM. Control: no amendment added (no CC or no BC); CC_22: Coal char 22 Mg ha−1; BC_22: Biochar 22 Mg ha−1; CC_44: Coal char 44 Mg ha−1; BC_44: Biochar 44 Mg ha−1.

3.2. Soil Chemical Properties and Nutrient Concentration

Selected soil chemical properties and nutrient concentrations of corn field plots after applying soil amendments with and without FM are presented in Table 6 and Figure 4. No significant effect of amendments was observed on soil pH, CEC, N, P, K, Ca, and Mg (Tables 5 and 6). Manure application had a significant effect on P, K, Ca, and Mg concentration in soil. We observed changes in pH, CEC, N, K, and Ca in 2022 compared to 2021. Further, we observed an interaction effect of amendment and manure application on the organic matter content of soil (Table 5, Figure 4A). The highest OM was observed in CC_44 in both manure and no manure treatments. There was amendment and year interaction for OM and EC (Table 5, Figure 4B,C). OM was higher in CC_44 in 2021 and 2022. For EC, there was no significant difference between amendments in 2021, but CC_44 had the highest EC in 2022, which was comparable with BC_22 0FM and BC_44 +FM.

Table 6. Post hoc test results of soil properties that did not have significant interaction among fixed effects from 2021 to 2022.

Fixed Effects		pH	CEC	NO_3-N	P	K	Ca	Mg
		(1:1)	(meq 100 g^{-1})		--------------------(mg kg^{-1})--------------------			
Manure	+FM	7.9 a	19 a	85 a	189.3 a	778 a	2909 a	330 a
	0FM	7.9 a	18 a	59 b	48.6 b	436 b	2787 b	289 b
Year	2021	8.0 a	20 a	97 a	129 a	649 a	2962 a	313 a
	2022	7.7 b	18 b	47 b	108 a	564 b	2734 b	305 a

Means followed by the same letters within columns are not statistically different ($p > 0.05$, *Fisher's LSD test*). 0FM: without FM; +FM: with FM.

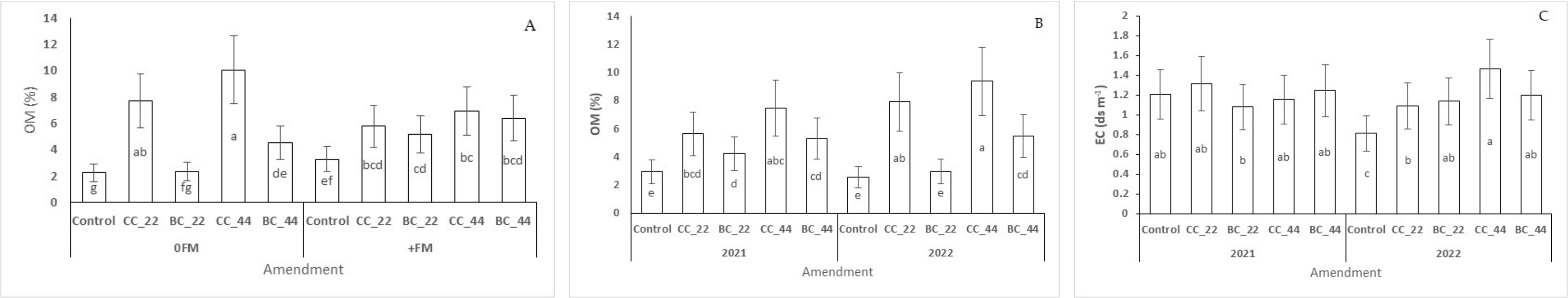

Figure 4. Post hoc test results of soil properties with significant two-way interaction among fixed effects from 2021 to 2022. Means followed by the same letters within columns are not statistically different ($p > 0.05$, *Fisher's LSD test*). (**A**) Impact of interaction between amendments and manure application on soil organic matter (OM) content. (**B**) Impact of interaction between amendments and year on soil organic matter (OM) content. (**C**) Impact of interaction between amendments and manure application on soil electrical conductivity (EC) content. 0FM: without FM; +FM: with FM. Control: no amendment added (no CC or no BC); CC_22: Coal char 22 Mg ha^{-1}; BC_22: Biochar 22 Mg ha^{-1}; CC_44: Coal char 44 Mg ha^{-1}; BC_44: Biochar 44 Mg ha^{-1}.

3.3. Soil Water-Holding Capacity

Figure 5 shows the soil WHC measured in 2022 for various soil amendment treatments with and without FM application. Soil WHC ranged from 49 to 67% when amendments were applied without FM. It ranged from 56 to 68% when amendments were applied with FM. The control plots without any amendments had a lower WHC for both +FM and 0FM, except for BC applied at 22 Mg ha^{-1} 0FM. Treatments incorporating FM exhibited an increased WHC when BC was applied at 44 Mg ha^{-1}, which is significantly higher ($p < 0.05$) from the treatment with no amendments. In contrast, CC applied at 44 Mg ha^{-1} showed a considerable improvement in soil WHC compared to the control. There was no significant effect of FM application on WHC.

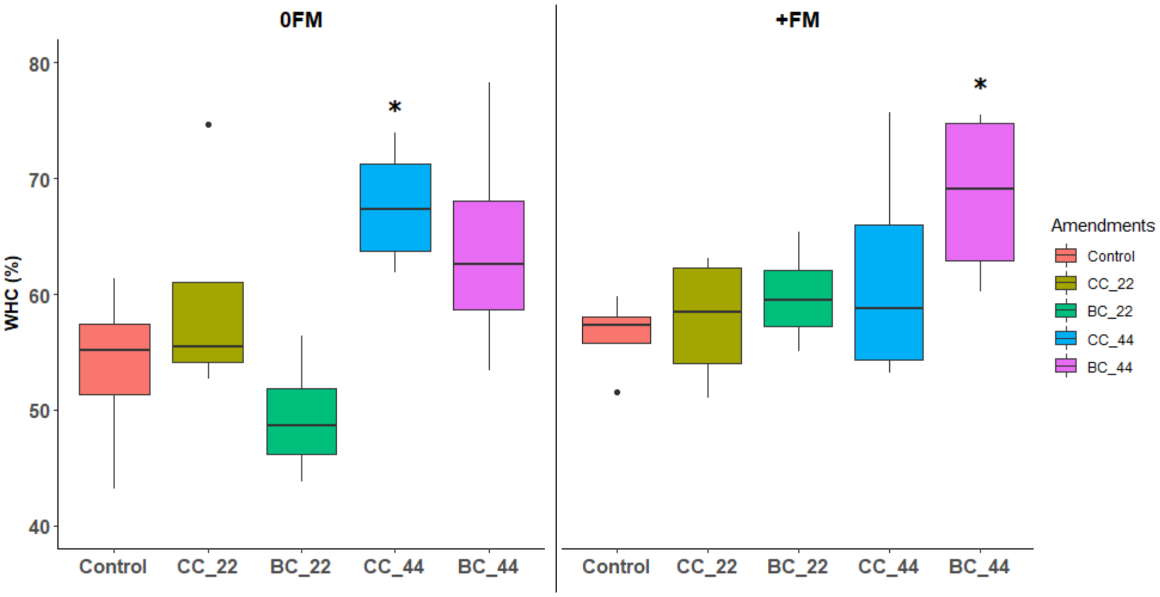

Figure 5. Soil water-holding capacity (WHC) of treatments with different amendments in combination with or without FM in 2022. Asterisk (*) indicates treatments with significantly higher WHC compared to the control. Dots (·) observed above or below the boxplot indicate outliers. 0FM: without FM; +FM: with FM. Control: no amendment added (no CC or no BC); CC_22: Coal char 22 Mg ha^{-1}; BC_22: Biochar 22 Mg ha^{-1}; CC_44: Coal char 44 Mg ha^{-1}; BC_44: Biochar 44 Mg ha^{-1}.

4. Discussion

This study supports the hypothesis of an increase in crop yield when CC and BC are applied with FM to agricultural soil. Two-year corn grain yields for the years 2021–2022, without FM (0FM) and with FM (+FM), indicated that CC and BC co-applied with FM can result in significantly greater corn grain yield than the no char control. In this study, FM alone treatment resulted in 11 and 7% less corn grain yield than CC_22 with FM and BC_22 with FM treatments, respectively. It can be associated with the synergistic effects from the combination of FM with chars, where chars might increase retention of mobile nutrients like NO_3-N in soil, where FM could have provided additional nutrients to increase corn yield. Furthermore, chars could decrease soil bulk density and increase soil porosity, which facilitates plant root expansion, resulting in more nutrient uptake by plants. A recent study [20] reported reduced bulk density by 3 to 31% and increased porosity by 14 to 64% when BC was applied as a soil amendment. BC combined with FM increases root volume and root surface area, facilitating greater nutrient uptake and incredible plant growth [54]. Previous research documented BC used with FM or compost as a soil amendment enhances soil properties and C content, increasing soil microbial community biomass, nutrient availability, and efficiency of nutrient use [55,56]. Similarly, another study [57] reported that FM and BC significantly contributed to crop yield and quality by improving soil fertility. However, attention should be kept on harmful elements in FM, such as antibiotics given to animals that do not metabolize in the animal's body and can be excreted in urine [58]. The salt content of FM is a much more common issue, especially in semiarid soil. The average yield in high application rate chars added with FM (CC_44 and BC_44) did not significantly increase corn yield compared to the control. Previous studies reported a decrease in nutrient supply in high BC application rates in sandy soils due to the immobilization of nitrogen with the high adsorptive capacity of BC [59,60]. Additional nutrients may need to be supplied to prevent yield inhibition due to the high application rate of chars that can adsorb many plant essential nutrients [61]. Our data from high BC application in the present study (BC_44) showed that average corn yield decreased, which aligns with the previous study results [62] that mentioned a decrease in aboveground corn biomass yield by 37% at a high application rate of BC (72 Mg ha^{-1}) in sandy soil; however, no decrease in yield was found when supplied sufficient additional mineral N fertilizer according to local agriculture practice. This study's results suggest the application rates of CC and BC are less than 22 Mg ha^{-1} in the farmland. However, further studies are required to find the optimal application rates of chars in the agroecosystem.

The year 2021 demonstrated a greater yield in all treatments, including no amendment-added control. One reason for this decrease in corn grain yield could be weather variation across the year. Figure 1 exhibited significantly greater rainfall in June 2021 than in June 2022. Rainwater contains nitrates, which could have supplied additional nitrogen for corn growth at the early growth stage, and that could result in a more extensive leaf area to capture available solar radiation. This could have produced more corn plant biomass in 2021 to produce more yield. There was an overall effect than the treatment-specific increase in grain yield.

The impact of CC and BC application on soil chemical properties has had mixed results. Treatments in which CC or BC were used in the first year of this study did not show a difference in soil pH across the treatments, and this indicates that the pH buffering capacity of soil is very high or application rates were not great enough to alter soil pH. However, a significant decrease in soil pH level was observed one year following the application in CC_22 and CC_44 treatments compared to the control in 0FM treatments. Similarly, soil pH in BC_22 and BC_44 treatments also decreased in 2022. This result aligns with a study [58] where BC decreased soil pH in sandy desert soil. Similar results were observed in the studies where soil pH was significantly decreased after BC application in alkaline soils [61,63,64]. Results from a previous study [65] indicated that a water-leaching experiment on BC prepared from rice husk removed 15 cmol$_c$ kg^{-1} base cations and reduced the pH by 0.2 units, from 8.4 to 8.2. Furthermore, the cacao shell BC removed 159 cmol$_c$ of base cations kg^{-1} due to water leaching and its pH dropped from 9.8 to 9.6. The water-leaching experiment showed a removed alkalizing effect on both BCs. A similar leaching effect might have happened in our CC and BC treatments. However, a long-term and detailed study is required to evaluate the effect of chars on soil pH. If the decrease in soil pH was due to CC and BC application, the pH of alkaline soils in semiarid and dryland agroecosystems might benefit.

Soil EC was not affected in the first cropping year with char applications in both +FM and 0FM treatments; however, it significantly increased after a year of amendment application in the soil. This increase in soil EC over the time of char application also verified the results of previous studies [66,67].

This study's results demonstrated that CC and BC increased SOM content in both years compared to non-amended control soil. This supported our hypothesis of SOC improvement with the application of CC and BC, which can be due to the high SOC content of both char materials. A study by Blanco-Canqui et al. [18] reported that a higher char (coal combustion residue) application rate (67.3 Mg ha^{-1}) increased soil SOC concentration by 56% compared to control soil. A similar study on BC reported that an application rate of 20 Mg ha^{-1} resulted in a significant increase in SOC, while the lower rate of 10 Mg ha^{-1} did not significantly affect it [68]. In some char +FM treatments, SOM decreased in the second year, possibly because of the decomposition of FM's organic matter, as we applied soil amendment materials only in the first year. BC treatments showed lower OM content relative to CC treatments, which could be because of the larger particle size of BC than CC, indicating that fine particle-size soil amendment materials can be mixed well with soil and be more reactive in the soil.

Soil CEC was not increased with the increase in OM in the 0FM CC- and BC-treated plots, which was relatively stable in both years. Increased OM on treated soils did not justify the treatments' CEC, which may be due to the recalcitrant C in the char materials (lack of labile C). However, BC applied with FM at a low rate (BC_22) resulted in significantly increased CEC in soil compared to the FM alone treatment in 2021. In the first year of char application, it appeared that all the FM co-applied with CC and BC treatments resulted in greater soil CEC, which could be due to the labile C provided by the FM application. The presence of many charged functional groups in the organic matter of FM could be a major factor in the rise in CEC [69], and the high surface area of BC could have led to absorb the FM's organic matter on its surface [70]. Total CEC is primarily associated with SOM in all soil types [71]. Previous study results also indicated that BC combined with FM resulted in a 4% increase in CEC compared to BC and NPK fertilizer addition [72]. A similar study [73] found a significant increase in CEC after applying BC in acidic soil. Results of our soil tests after the soil amendments were applied in the field showed that the percent base saturation composition of CEC ranges from 2.6 to 5.1% for Na^+, 12 to 14.5% for Mg^{2+}, 71.6 to 80.7% for Ca^{2+}, and 4.8 to 11.5% for K^+ in the soil test. It indicates that Na^+ occupies the least fraction of the total exchange sites (CEC), indicating no salinity effects on soil with these soil amendment materials. The level of Na^+ less than 15% on the exchange site is desirable in the soil test [74].

In CC- and BC-treated soils, NO_3-N exhibited a higher concentration, especially in +FM treatments, than in 0FM and the control treatment, which could be associated with the co-effect of an additional supply of N from the FM and nutrients adsorbed or retained by the char materials in the soil. FM-added plots had more NO_3-N than 0FM plots with chars or without chars. Increased SOM due to FM, CC, or BC could have played a vital role in nutrient sorption as OM helps to improve a wide range of soil properties like an increase in CEC, buffering capacity, water retention, soil microbial diversity, and structural stability. Similar studies on BC reported that retention of NO_3-N and NH_4-N in the root zone increased by 33 and 53% in agricultural sandy loam soil [75]. The results of this study correlate with the previous study [76], which reported reduced leaching of NO_3-N by 7.0–15.4% in the BC-applied silt loam cropland soil. The sandy loam soil of this experimental site may not have retained the applied fertilizer in the control plots where BC or CC was not applied.

In both growing seasons, 2021 and 2022, soil P and K nutrients were significantly greater in the +FM treatments than in the control and char-only treatments (Table 6), which is in agreement with the results from previous studies [36,77,78]. This can be attributed to the nutrient-holding capacity of porous char materials that could have retained more significant P and K supplied from the FM in the soil. Moderate P fertilization can improve corn growth and soil microbial population including arbuscular mycorrhizal fungi which are important for increasing nutrient uptake [79]. Inconsistent effect was determined for Ca content in the soil. Overall, soil Ca was unaffected by the CC and BC application, though it decreased when FM was added to the treatments in 2021. However, no significant changes in Ca content were noticed after a year of amendments application in the soil. Soil Mg was found to be relatively unaffected by the CC and BC application. In the second growing season, the Mg increased in +FM treatments, which could be associated with additional Mg supply from FM [77,80]. In the first year of the char applications, nutrients could have been absorbed by chars [81,82] and, as time passed, they could have gradually been released into the soil environment over time.

As expected, the impact of CC and BC in soil WHC was significantly greater with the greater rates of char application. Although statistically insignificant, we found greater soil moisture content in most of the char-containing treatments compared to the control, except for the BC_22 treatment. Maximum soil WHC was obtained in BC_44 +FM treatment, followed by CC_44 0FM treatment Figure 4. Similar results regarding soil WHC were found from previous BC studies [46], which reported that soil WHC increased by 62.1% and 37.1% for the small and large particle size BC, respectively, at a 20% application rate in sandy loam soil. That study also mentioned the reduced gravimetric soil WHC by 13.4 and 12% in the BC application rate of 5% for small and large particle sizes, respectively. Small particle size chars seemed more effective for soil WHC, and this also signifies that a lower application rate of chars may be inadequate for significant water-holding capacity enhancement, which was confirmed in our BC treatments as well. A recently published review paper documented increased soil WHC with BC as a soil amendment and reported that soil texture and particle size of BC influence the degree of effect on WHC [83]. With a high surface area and more excellent pore spaces, CC and BC might have provided more soil micropores to hold more water. According to previous studies [84,85], diverse and complex structures were found with many pores and channels of different diameters when in scanning electron microscopy (SEM) images of BC at different magnifications.

5. Conclusions

Results from this two-year field study in irrigated corn indicate that a moderate rate application of CC and BC (22 Mg ha^{-1}) could provide a positive impact on corn grain yield than a high application rate (44 Mg ha^{-1}) when co-applied with FM. SOM increase in the char-added plots signifies the long-term soil health benefits of using CC and BC as soil amendments, which may enhance soil physical, chemical, and biotic properties over time, resulting in higher plant growth and crop yield. A more significant amount of nitrate in chars with FM treatments may reflect the nitrate absorbed within the microporous structure of CC and BC. Though it might take several years to understand the influence of stable C from char materials on soil health, some enhanced soil properties, such as increased OM and increased WHC within a short application period, shed light on the potential use of CC as a soil amendment. Soil WHC can be associated with increased crop yield and the retention of nutrients dissolved in the water. The results of this field study indicate that CC could be a suitable soil amendment like BC in the low C sandy loam soils in semiarid areas. However, multiyear studies are required to understand the interaction of char materials within soils. Therefore, there is still a need for more data, especially from long-term field trials, to confirm and validate the results on the effectiveness of CC and BC on diverse soil types and different agro-climatic zones to improve crop productivity and soil properties.

Author Contributions: Conceptualization—R.B.T. and P.D.S.; Funding Acquisition—P.D.S.; Methodology—R.B.T. and P.D.S.; Data Collection—R.B.T., S.X.T., B.A. and S.B.; Investigation—R.B.T. and P.D.S.; Data Curation—R.B.T. and C.S.; Formal Analysis—R.B.T. and C.S.; Visualization—R.B.T., C.S. and D.P.; Software—C.S. and R.B.T.; Validation—P.D.S. and D.P.; Writing—Original Draft Preparation—R.B.T., S.B. and C.S.; Writing—Review and Editing—P.D.S., D.P. and B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by School of Energy Resources, University of Wyoming: 1252.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: We thank the School of Energy Resources, University of Wyoming, for financially supporting this study through the Carbon Engineering Initiative Grant. We also acknowledge Atlas Carbon LLC for providing CC, and Biochar Now for providing BC for this study. We also thank Carrie Eberle, Kevin D. Madden, Blaine Alan Magnuson, and all crew members of the Sustainable Agriculture Research and Experiment Center (SAREC), Lingle, WY, for their support during the fieldwork setup.

Conflicts of Interest: The authors declare no conflicts of interest.

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